EUROPEAN
SEISMOLOGICAL
COMMISSION

XXIV General Assembly
1994 September 19-24
Athens, Greece

Proceedings
and Activity Report 1992-1994
Volume I

University of Athens
Faculty of Sciences
Subfaculty of Geosciences
Department of Geophysics & Geothermy

BODY WAVE MODELLING AND SOURCE PARAMETERS DETERMINATION OF THE 23 MAY 1994 CRETE EARTHQUAKE

P. Papadimitriou, J. Kassaras, K. Makropoulos, J. Drakopoulos
Department of Geophysics, University of Athens, 15784 Athens, Greece

ABSTRACT

The Hellenic Trench, convergence zone between Eurasia and Africa, is characterized by a rate of about 6cm.yr^{-1}. Several moderate earthquakes have been located in the south and southwest of Crete, along the Hellenic trench. The focal depths vary between surface and 60 km and the mean slip-vector direction is N22°. The focal mechanisms of these events indicate mainly reverse faulting.

On May 23, 1994 an earthquake of Ms=6.2 occurred near the northern coast of Crete. In this region no large events have been recorded during the last thirty years. Therefore the estimation of the source parameters by teleseismic body wave analysis could not be performed. The only available seismological data for the area of northern Crete, other than the earthquake catalogues, have been provided by microearthquake studies in southern Aegean sea. The recent earthquake of Crete is one of the largest teleseismically recorded in the area. Body wave modelling is applied in this study to determine the source parameters of the earthquake. The determined fault plane solution indicates thrust mechanism with a low angle NE dipping plane and a focal depth at 80km. Considering source parameters calculated also by body wave modelling and microearthaquake results from the experiment of 1988, we conclude that the recent earthquake occurred in the Wadati-Benioff zone, the dip of which is estimated 32° toward the NE, within the African lithosphere and in the bending zone where the frictional process yields an important shear field.

INTRODUCTION

The African and Eurasian lithospheric plates are converging at about 1cm/yr with a N-S orientation (Argus et al.,1989). The Hellenic Trench subduction system, belt of rapid deformation due to the convergence between the two plates in the eastern Mediterranean region, has been a subject of various recent discussions, which attempt to describe the geometry of the motion. McKenzie et al., (1978), based on slip vectors of earthquakes' fault plane solutions and field data, suggest that the convergence rate is at least 70mm/yr in a N202° direction. Le Pichon and Angelier (1979), estimate an average rotation rate of 2-3°/ Myr, predicting velocities of about 10mm/yr at the western edge of the trench, increasing to about 40mm/yr eastwards. Jackson and McKenzie (1988), estimated the convergence velocity of about 100mm/yr and the age of subduction to 5Myr, in agreement with Mercier et al. (1976). Ekstrom and England (1989), calculated the seismic moment release, estimating the azimuth of the velocity vector south of Crete at 163°.

The inferred from seismicity Benioff zone (Comninakis and Papazachos 1980; Martin 1988; Besnard 1991; Hatzfeld and Martin 1992), is not parallel to the trench, dipping gently in the west beneath Peloponnesus steepening 200km from the trench, while being steeper beneath the sea of Crete (Hatzfeld et al. 1993a). Taymaz et al., (1990), calculated the source parameters of teleseismically recorded intermediate moderate earthquakes located near Crete by body waveform modelling, estimating that the slab is striking about N280°, dipping about 35° towards the northeast, while the relative motion between the two plates constrained by the slip vectors azimuth is N25±12°.

Most of the reliably determined fault plane solutions of moderate intermediate earthquakes are located along the trench, while in the north of it there is no evidence for large events during the microearthquakes recorded during a two months' experiment in the Aegean in 1988 (Hatzfeld et al. 1993a; Hatzfeld et al. 1993b; Besnard 1991). The May 23, 1994, moderate earthquake near the northern coast of central Crete, is the only large event in the specific area, for which the source parameters can be teleseismically determined. In this paper, considering the most reliable intermediate earthquake data available for the area of Crete (ISC locations M>5; best located events and focal mechanisms obtained during the 1988 microseismicity campaign; focal mechanisms computed by waveform inversion methods; the results of the recent Crete earthquake analysis), we are attempting to contribute to the definition of the slab geometry and the stress field distribution of the area of Crete.

DATA AND METHODOLOGY

Body wave inversion applied on teleseismic recordings of IRIS data center distribution is used to determine the source parameters of the May 23, 1994, Crete earthquake. The shape and amplitude of the body waves recorded at epicentral distances between 15 and 90° are compared with synthetic waveforms. For epicentral distances between 15 and 30° we use the Gaussian Beam Sum-

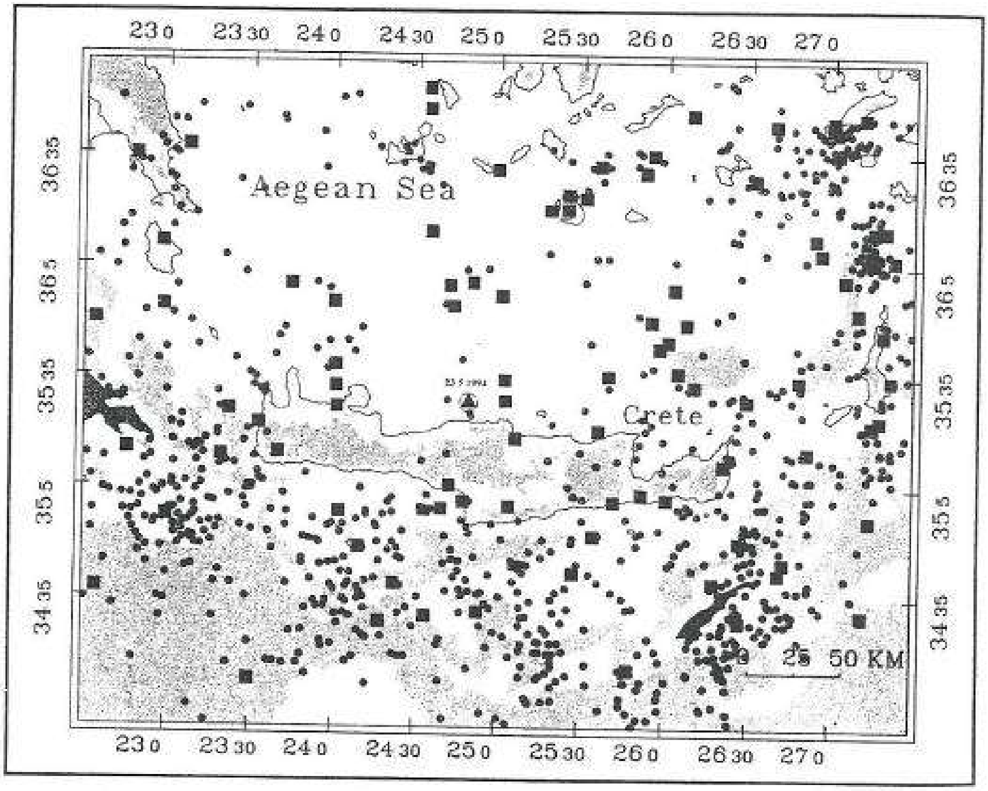

Figure 1. Map of large earthquakes occurred in the area until 1994. Historical data until 1963 are plotted in squares, while circles denote ISC locations during 1963-1994, M>4. The larger symbol represents the epicenter of the under study event.

mation Method (GBS) and the EΠ86 velocity model (P. Papadimitriou, 1988). At these distances no standard methods are valid due to the presence of the upper mantle triplications. The GBS method calculates the Green's function, which represents the response of the upper mantle, as proposed by Madariaga and Papadimitriou (1985), using a constrained velocity structure. For epicentral distances between 30 and 90° we use standard methods. The synthetic seismograms are composed by generating direct (P or S) and reflected at the free surface (pP and sP or sS) phases radiated by a point source, assuming a ray propagation in a homogeneous half-space medium (the body waves travel mostly in the lower mantle and the Green's function is simulated as a delta function).

The determined source parameters are compared with those concerning earthquakes located in the surrounding area, estimated by using also modelling techniques (P. Papadimitriou, 1990; Taymaz et al., 1990; Beiber et al., 1990). In addition, source parameters from microearthquake studies (Hatzfeld et al., 1993a,b; Chabalier et al., 1992) are considered, to discuss about the geometry of the slab and the role of the recent earthquake occurred on May 23, 1994.

Hypocentral Location				
Lat.: 35.50	Long.:24.78		Depth: 80km	
Station	**Distance**	**Azimuth**	**I_h**	**I_o**
ESK	27.60	324.6	42.0	28.8
CCM	85.85	314.6	21.5	15.3
CHTO	66.69	83.0	28.5	20.0
COL	79.77	356.8	23.8	17.0
KONO	26.11	342.4	42.3	29.0
MAJO	85.33	47.9	21.6	15.4
PAB	23.40	288.6	45.3	30.8

Table 1. Hypocenter location of the 23/5/1994 event, the epicentral distances in degrees, azimuths and the angles of incidence-emergence for each station used.

DETERMINATION OF SOURCE PARAMETERS

We retrieved teleseismic digital records from IRIS data center distribution to determine the source parameters of the event. Synthetic seismograms were composed using displacement waveforms sampled at 4 points per seconds. Because of high frequencies presence in the content of the observed seismograms, for each record we deconvolved the instrument response and applied a broad-band Butterworth filter. The May 23, 1994, Crete earthquake has a moderate magnitude and thus, only seven recordings being of good quality are used (table 1), the three of them reported at epicentral distances less than 30°. Synthetic seismograms are generated for a given epicentral distance, depth and focal mechanism and then they are compared to the corresponding observed ones. The best fit between the observed and calculated seismograms is obtained by direct matching.

The body wave modelling is presented in figure 2. The final solution reveals thrust faulting in a depth of 80km and a trapezoidal source time function of 5 seconds duration. The fitting between the observed and the synthetic seismograms is well established at 80km depth, where the pP and sP reflected phases are very clear. The fault plane solution is essentially constrained by the PAB, ESK and CHTO stations because they are situated very close to the nodal planes which control the shape and the amplitude of the direct and reflected phases. In figure 2, we also indicate the epicentral distance for each station in degrees and the value of the seismic moment. The mean value of the seismic moment of the earthquake is 3.2×10^{24} dyn-cm.

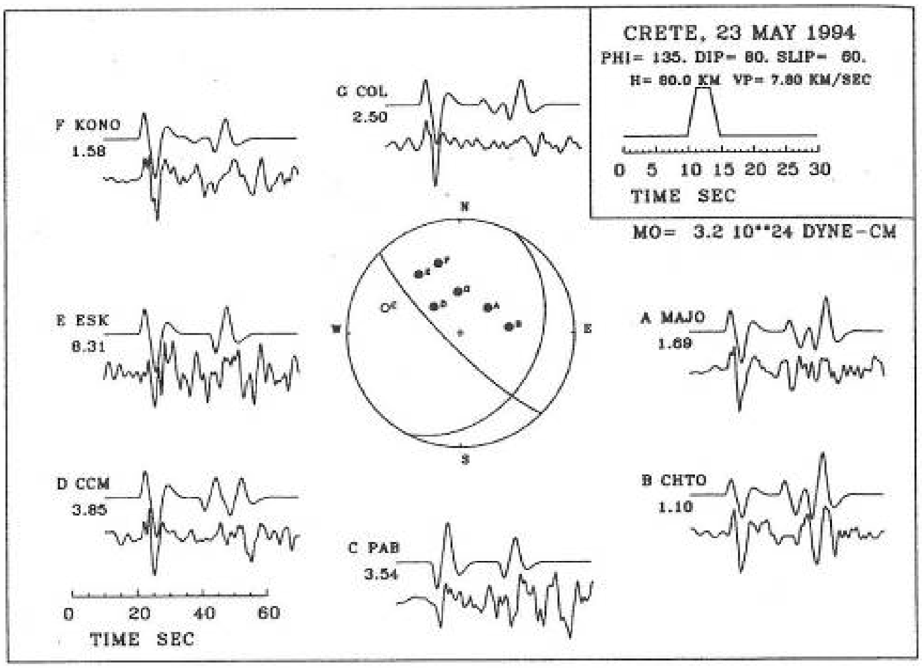

Figure 2. Broad band observed (lower plotted) and synthetic (upper plotted) P waveforms, recorded at teleseismic distances, of the May 23, 1994, Crete earthquake. The synthetics were calculated for a fault plane with strike=135°, dip=80°, rake=60° and focal depth h=80km. The source time function is simple trapezoidal with a duration of 5secs., and the seismic moment $M_o=3.5\times10^{24}$ dyn-cm.

DISCUSSION

In figure 1, the locations of large earthquakes occurring in the area of Crete until 1994 (historical and ISC catalogues data, M>4) are plotted. In 1988, a temporary network of 82 portable seismographs was installed for seven weeks over the islands of the southern Aegean Sea and Peloponnesus (Hatzfeld et al., 1993a). During this period, 766 events were recorded, among which 72 have been located deeper than 40 km, with 47 of them located better than 20 km (Hatzfeld et al., 1993b). Comparing the distribution of large events (fig. 1) and microearthquakes (fig. 3), we obtain a similar pattern, with the majority of the epicenters being located along the trench.

The focal mechanisms constrained by modeling methods (Lyon-Caen et al., 1988; Kiratzi & Langston, 1989; P. Papadimitriou et al., 1990; Taymaz et al., 1990; Beiber et al., 1990) and CMT solutions are presented in figure 4. In this figure, we additionally plot fault plane solutions of the 1988 experiment microeartquakes located north of Crete, determined by using first motion P-waves' polarities (Hatzfeld et al., 1993b). The selected micro-earthquakes are included in this paper because their depth distribution exceeds the depth of large earthquakes limited at 40-60 km, except in the case of the 23rd of May, 1994, earthquake, for which the depth is estimated at 80 km. Another reason for using the small events is their higher location precision, as they are recorded by a local

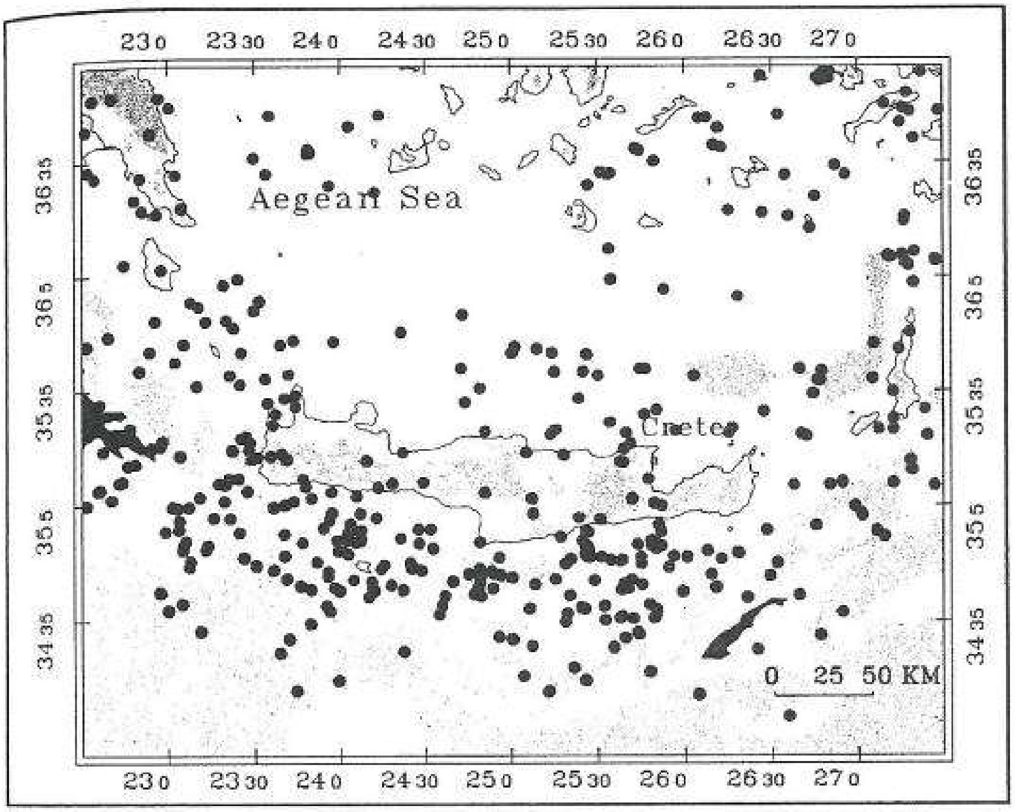

Figure 3. 1988 experiment, microearthquakes' locations.

network, compared to the locations included in the ISC catalogues, estimated using teleseismic recordings. The microearthquake activity reveals only a part of the brittle deformation in time and space, thus it is obvious that the rupture mechanisms of large events could be different and more complex.

The distribution of focal mechanisms along the Hellenic Arc present a complex pattern (figure 4). Normal faulting in N-S direction is observed along the southern edge of the Aegean with a depth distribution from surface to 20 km (Hatzfeld et al., 1993a; Chabalier et al. 1992). This crustal deformation represents an extension parallel to the arc above the subduction zone (Lyon-Caen et al., 1988). Along the Hellenic arc, reverse focal mechanisms are observed with a depth distribution between 20 and 60 km. Taymaz et al., (1990), distinguish the reverse type of mechanisms in three groups: a) low-angle thrust faulting trending in E-W direction b) high-angle reverse faulting trending in E-W direction and c) high-angle reverse faulting with strike-slip motion. The slip vector of groups a and b have both a similar NE direction and nodal planes dipping north. In this configuration, the low-angle thrust mechanisms could be associated to a frictional interface between the subducting African plate and the overriding Aegean lithosphere with the high-angle reverse faulting representing splay faulting off this master thrust surface. Fault plane solutions constrained by P-wave first motion polarities located at a depth between 40km and 130km have approximately similar mechanisms with a and b groups.

A cross section across the Trench, in N22° direction is presented in figure 5.

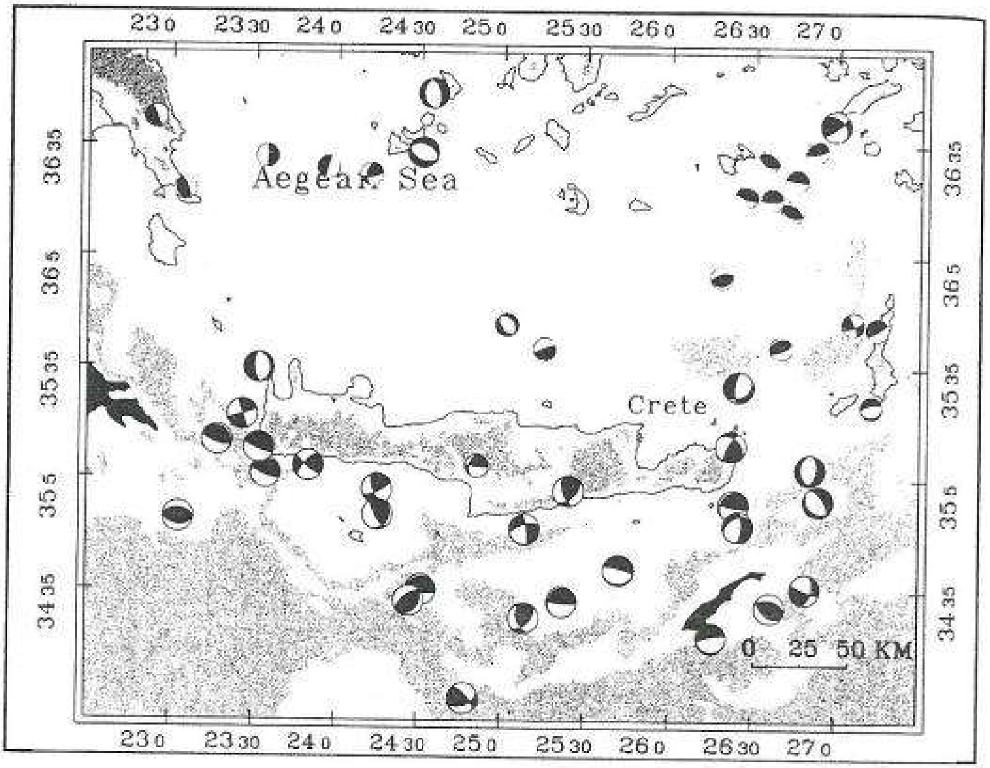

Figure 4. Fault plane solutions available for the area (see text). The large events are represented with the larger focal sphere.

The deep-focus May 23, 1994 earthquake occurred in the Wadati-Benioff zone within the lithospheric slab descending into the mantle. The earthquake is located in the bending zone where the frictional process yields an important shear field. The focal mechanism fits the shallow dipping Wadati-Benioff zone, for wich the dip is estimated at 32° towards the NE. The N-S trending T-axis is aligned to the subducted slab, while the E-W trending P-axis is parallel to the strike of the Hellenic arc south of Crete.

CONCLUSION

The source parameters of the May 23, 1994 Crete earthquake were calculated using teleseismic body-wave analysis by the application of GBS method and the EΠ86 velocity model. The focal mechanism of the event reveals thrust faulting with a N-S trending T-axis, aligned to the subducted slab and an E-W trending P-axis, parallel to the Hellenic arc south of Crete. The depth of the source was estimated in 80 km, within the subducted lithosphere. The considered source parameters for large earthquakes in the area estimated by body wave modeling and those obtained by microeartquake analysis, well define a shallow dipping, of 32° towards the NE, Wadati-Benioff zone. According to this configuration, the studied event occurred within the frictional zone, where the largest intermediate earthquakes along the Hellenic arc were produced during the last years.

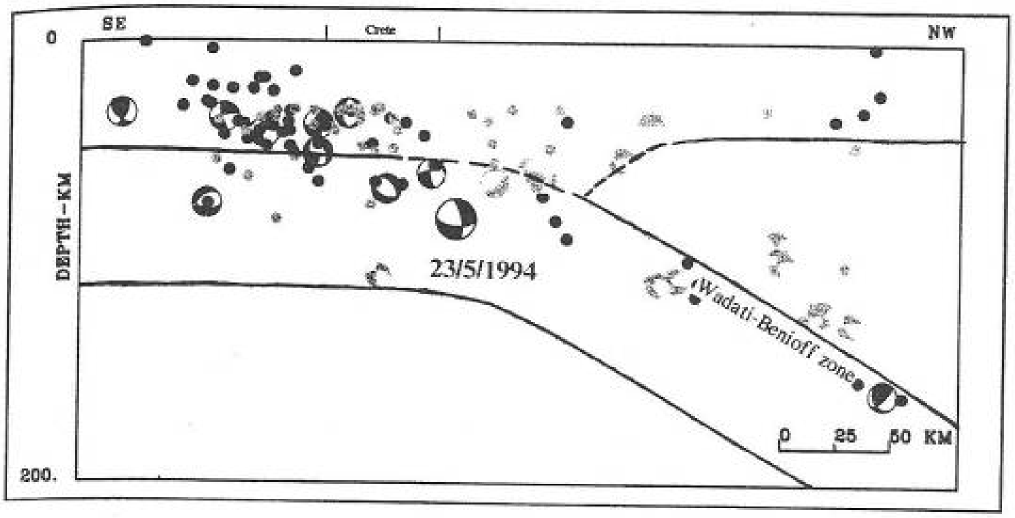

Figure 5. Cross section across the trench, in N22° direction. ISC locations, 1963-1994, M>5 and focal mechanisms constrained by waveform inversion methods (see text), are denoted in black. The microearthquakes' hypocenters located during the 1988 experiment, (z>30km, erx<20km), are denoted in gray.

REFERENCES

Beiber M., Wyss M. and Kind R., 1990. Inversion of source parameters for subcrustal earthquakes in the Hellenic Arc, *Geophys. J. Int.*, **103**, 439-450.

Besnard, M., 1991. Sismotectonique de l'arc égéen, résultats d'une campagne de microsismicité, *Thése*, Universitè J. Fourier, Grenoble.

Chabalier, J.B., Lyon-Caen, H., Zollo, A., Deschamps, A., Bernard, P. & Hatzfeld, D., 1992. A detailed analysis of microeartquakes in westrem Crete from digital three-component seismpgrams. *Geophys. J. Int.*, **110**, 347-360.

Comninakis, P. E. & Papazachos, B. C., 1980. Space and time distribution of the intermediate focal depth earthquakes in the Hellenic arc, *Tectonophysics*, **70**, T35-T47.

Ekstrom, G. & England, Ph., 1989. Seismic strain rates in regions of distributed continental deformation, *J. geophys. Res.*, 94, 10231-10257.

Jackson, J. A. & McKenzie, D., 1988. The relationship between plate motions and seismic moment tensors, and the rates of active deformation in the Mediterranean and the Middle East, *Geophys. J. Int.*, **93**, 45-73.

Hatzfeld, D. & Martin. Ch., 1992. The Aegean intermediate seismicity defined by ISC data, *Earth planet. Sci. Lett.*, **113**, 267-275.

Hatzfeld, D., Besnard, M., Makropoulos, K., Hatzidimitriou, P., Panagiotopoulos, D., Karakaisis, G., Deschamps, A. & Lyon-Caen, H., 1993a. Subcrustal microearthquake seismicity and fault plane solutions beneath the Hellenic arc, *J. geophys. Res.*, **98**, 9861-9870.

Hatzfeld, D., Besnard, M., Makropoulos, K. & Hatzidimitriou, P., 1993b. Microearthquake seismicity and fault plane solutions in the southern Aegean and its geodynamic implications, *Geophys. J. Int.*, **115**, 799-818.

Kiratzi, A.A. & Langston, C.A., 1989. Estimation of earthquake source parameters of the May 4, 1972 event of the Hellenic arc by the inversion of waveform data, *Earth Planet. Inter.*, **57**, 225-232.

Le Pichon, X. & Angelier, J., 1979. The Hellenic arc and trench system: a key to the neotectonic evolution of the Eastern Mediterranean region, *Tectonophysics*, **60**, 1-42.

Lyon-Caen, H., Armijo, R., Drakopoulos, J., Baskoutas, J., Delibasis, N., Gaylon, R., Kouskouna, V., Latoussakis, J., Makropoulos, K., Papadimitriou, P., Papanastassiou, D. & Pedotti, G., (1988). The 1986 Kalamata (S Peloponessus) earthquake: detailed study of a normal fault, evidences for east-west extension in the Hellenic Arc, *J. Geop. Res.*, 93, 14967-15000.

Madariaga, R., & papadimitriou, P., 1985. Gaussian Beam modelling of upper mantle phases, *Ann. Geophys.*, **6**, 799-812.

Martin, Ch., 1988. Géométrie et cinématique de la subduction égéene, structure en vitesse et atténuation sous le Péloponnése, *Thése*, Université J. Fourier, Grenoble.

Mercier, J. L., Carey, E., Philip, H. & Sorel, D., 1976. La néotectonique plio-quaternaire de l'arc égéen externe et de la mer Egée et ses relations avec la sismicité, *Bull. Soc. Géol. France*, **7**, 355-372.

McKenzie, D. P., 1978. Active tectonics of the Alpine-Himalayan belt: the Aegean Sea and surrounding regions, *Geophys. J. R. astr. Soc.*, **55**, 217-254.

Papadimitriou P., 1988. Etude de la structure du manteau superieur de l'Europe et modelisation des ondes de volume engendrees par les seismes egeens, Ph. D. thesis, Univ. of Paris.

Papadimitriou P., Makropoulos K., Drakopoulos J. and Deschamps A., 1990. Source parameters determination of the 21st of June 1984 moderate earthquake in western of Crete (Greece), proceedings of XXII General Assembly of the ESC.

Taymaz, T., Jackson, J. A. & Westaway, R., 1990. Earthquake mechanisms in the Hellenic Trench near Crete, *Geophys. J. Int.*, **102**, 695-732.